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POLARIZATION PROPERTIES OF THE GALILEAN SATELLITES OF JUPITER: OBSERVATIONS AND PRELIMINARY ANALYSIS

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ABSTRACT

We present new, detailed polarimetric measurements of the Galilean satellites of Jupiter with U, B, V, and R filters at phase angles ranging from 12° to nearly 0°. The polarization phase curves of Io, Europa, and Ganymede in the B, V, and R filters clearly show the presence of the polarization opposition effect in the form of a sharp peak of negative polarization centered at a very small phase angle of 0°.6–0°.7 and superimposed on the regular negative polarization branch. This phase angle is comparable to the width of the spikelike photometric opposition effect observed for Europa, thus indicating that both opposition phenomena are likely to be produced by the coherent backscattering mechanism. The U filter values of $|P_{\min}|$ for Io and Europa are close to 0.60% and 0.47%, respectively, and exceed the respective BVR values by a factor of almost 2. The BVR polarization for the trailing hemispheres of Io, Europa, and, especially, Ganymede is systematically stronger than for the respective leading hemispheres. For Callisto, the leading hemisphere polarization is significantly stronger than for the trailing hemisphere. The inversion angles for Io, Europa, and Ganymede are nearly wavelength independent and close to 10°.0, 8°.6, and 8°.8, respectively. The inversion angle for the trailing hemisphere of Callisto is also wavelength independent and is in the range of 12°–13°.

Subject headings: minor planets, asteroids — planets and satellites: individual (Jupiter) — polarization — radiative transfer

1. INTRODUCTION

It is known that because of geometrical constraints, ground-based polarimetric observations of most atmosphereless solar system bodies (ASSBs) are possible only at phase angles smaller than a few tens of degrees and often even less. However, such measurements are widely used as one of the most powerful remote-sensing techniques for studying and classifying physical characteristics of the surfaces of individual ASSBs and their groups and families.

In the 1960s and 1970s, a detailed set of measurements of the degree of linear polarization of the Galilean satellites at different phase angles, with a broadband filter centered at a wavelength of $\lambda = 550$ nm, was performed by Dollfus (1975). These measurements allowed him to determine the main polarization parameters of the satellites (we will discuss these later) and to compare them with laboratory polarimetric measurements of terrestrial samples. As a result, Dollfus concluded that the polarization observed for Europa is consistent with the reflection of sunlight from a water-frost surface, whereas parts of the Ganymede surface could be covered with frost and parts with darker rocky materials. Dollfus also reached some interesting conclusions about the origin of the surfaces of Io and Callisto.

At about the same time, a large volume of polarimetric data on the Galilean satellites in white light was obtained by Veverka (1971). He was the first to notice that the leading hemisphere of Callisto differs polarimetrically from the trailing one.

In 1972 and 1973, a series of polarimetric observations of the Galilean satellites in green light was performed by Gradie & Zellner (1973). They noticed that the polarization of Ganymede near zero phase did not tend to zero, as might be expected, but rather had a distinctly nonzero value.

The first series of multicolor polarimetric observations of the Galilean satellites in six broadband filters from 390 to 685 nm was performed by Botvinova & Kucherov (1980). These authors concluded that the polarization measured for all four satellites was essentially wavelength independent.

The most detailed multicolor polarimetry of the Galilean satellites in four spectral bands from 420 to 700 nm was performed in 1981–1988 by Chigladze (1985, 1986, 1987, 1989). Contrary to Botvinova & Kucherov (1980), he found that the minimum polarization value $P_{\min}$ was rather strongly dependent on wavelength. He also concluded that for all four satellites, the polarization at phase angles $\alpha < 1°$ changed sign from negative to positive and reached values of about 0.2%–0.3%. We will show later that in fact, the polarization at small phase angles remained negative but had the same absolute value as that measured by Chigladze.

To our knowledge, the above-mentioned papers complete the list of publications in which polarimetric investigations of the Galilean satellites have been carried out. The most comprehensive review of polarimetric observations performed in the 1960s and 1970s can be found in Veverka (1977).

In order to interpret polarimetric observations of the Galilean satellites and other ASSBs, many authors have performed laboratory polarimetric measurements of various natural and artificial samples, including lunar soils. This work was initiated by Lyot (1929) and is reviewed by Muinonen (1990, 1994) and Shkuratov (1994). An inter-

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esting laboratory investigation was performed by Geake & Geake (1990), who specifically studied polarization features characteristic of very fine alumina grains (grain sizes from 10 to 0.1 wavelengths in the visible) in order to develop a remote sensing technique for detecting the presence of such microscopic grains on the surface of ASSBs.

Typical polarization phase curves of ASSBs exhibit a negative polarization branch at small phase angles (hereafter, regular negative polarization branch) and a positive branch at middle phase angles (Fig. 1). Theoretical models of the negative and positive polarization branches were developed by Wolf (1975, 1980), Steigmann (1978), Shkuratov (1982), Kolokolova (1990), and Wolf & Dollfus (1990). Unfortunately, most of these models are semi-empirical and lack physical rigor.

Recently, Shkuratov, Opanasenko, & Melkumova (1989), Muinonen (1989, 1990), and Shkuratov (1991) suggested that coherent backscattering of light by fine regolithic grains on the surfaces of ASSBs might be the universal physical explanation of the regular negative polarization branch. However, Mishchenko (1993) has used the rigorous theory of coherent backscattering (Ozrin 1992) to show that this optical mechanism produces a sharp asymmetric peak of negative polarization at extremely small phase angles, rather than the usual, wide and nearly parabolic negative polarization branch with a minimum at a phase angle of several degrees. Mishchenko has called the sharp, coherent peak of negative polarization at nearly zero phase angles the "polarization opposition effect." Because of the rare occurrence of suitable planet configurations, the polarization opposition effect is difficult to observe. However, Mishchenko (1993) has recently reanalyzed polarization observations of Saturn's rings in the visible (Lyot 1929; Johnson et al. 1980) and demonstrated that the polarization

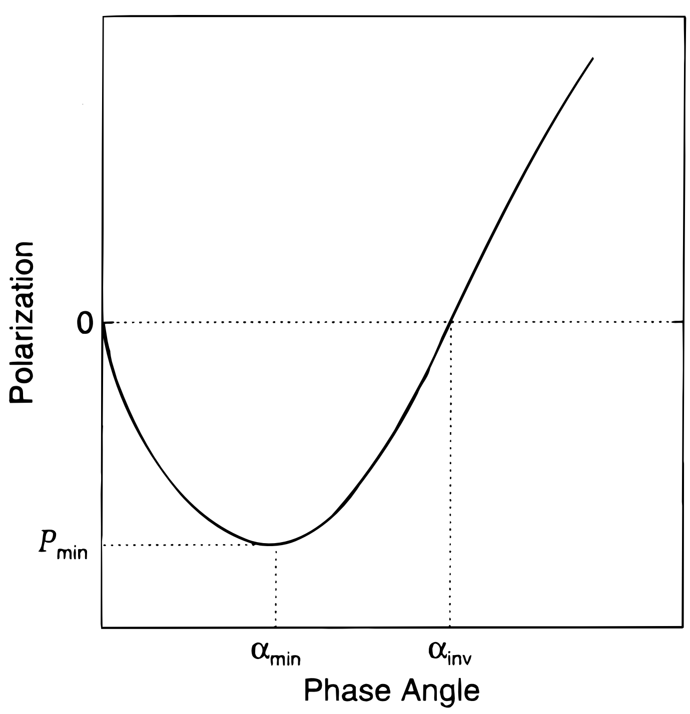

FIG. 1.—Typical polarization phase curve of atmosphereless solar system bodies. P_{min} is the minimum polarization value, α_{min} is the phase angle at which polarization reaches the minimum value, and α_{inv} (inversion angle) is the phase angle at which polarization changes sign.

opposition effect, superimposed on the regular negative polarization branch, can explain the peculiar behavior of the polarization phase curve of Saturn's rings near the opposition. Importantly, Mishchenko & Dlugach (1992) have shown that coherent backscattering also explains the photometric opposition effect exhibited by Saturn's rings at visible wavelengths.

In this paper we describe new, detailed polarimetric measurements of the Galilean satellites with U, B, V, and R filters at phase angles ranging from 12° down to nearly 0°. Our measurements for Io, Europa, and Ganymede clearly show the presence of the polarization opposition effect centered at about 0°.6–0°.7. This angle is comparable to the angular width of the unusually sharp photometric opposition peak observed earlier for Europa (Domingue et al. 1991; Thompson & Lockwood 1992), thus indicating that both phenomena are likely to be produced by the same mechanism. We compare our polarimetric measurements with other available data and describe the results of a preliminary data analysis. A more detailed quantitative interpretation based on the theory of coherent backscattering will be presented in a subsequent paper.

2. OBSERVATIONS

Polarimetric observations of the Galilean satellites were carried out from 1988 August to 1989 April in Tarija, Bolivia, and from 1989 November to 1991 February on Maydanak Mountain in Uzbekistan. In the two cases we used nearly identical spectropolarimeters installed in the Cassegrain focus of similar 0.6 m reflectors. These devices had two optical channels: a filter polarimeter and a spectropolarimeter with a diffraction grating. The first channel was used with filters close to the standard $UBVR$ Johnson system. The polarimeters and the measurement technique used are described in detail by Bugaenko & Gural'chuk (1985) and Gural'chuk, Kucherov, & Morozhenko (1986), therefore we will outline here only the most important characteristics of the spectropolarimeters. The devices had a light modulator consisting of a fixed Polaroid plate and a rapidly spinning phase retarder plate. This design allows one to minimize the errors caused by atmospheric scintillations, low-frequency changes of atmospheric transmissivity, and other sources, and to measure all components of the Stokes vector with equally high accuracy. The retarder in the spectropolarimeter installed in Tarija was a 127°-plate achromatic in the spectral range 360–750 nm which allowed a simultaneous measure of all four Stokes parameters, I, Q, U, V. The spetropolarimeter installed on Maydanak used a 180° plate and measured only the first three Stokes parameters, I, Q, and U. Separate detection channels were used to accumulate the β_I, β_Q, and β_U signals, which, for small linear polarization values, are related to dimensionless Stokes parameters $q = Q/I$ and $u = U/I$ as follows:

$$q \cong k\,\frac{\beta_Q}{\beta_I}\,, \quad u \cong k\,\frac{\beta_U}{\beta_I}\,, \tag{1}$$

where the factor k was equal to 1.96 and 1.57 for the 127° and 180° retarders, respectively. The degree of polarization and the position angle of the polarization plane in the instrumental reference system are expressed in the parameters q and u via the well-known formulae

$$p = \sqrt{q^2 + u^2}\,, \tag{2}$$

TABLE 1

POLARIMETRY OF IO

DATE UT	α (deg)	L (deg)	P (%) U	B	V	R
Bolivia (Tarija Observatory)						
1988 Oct 2.292	9.61	252	−0.61	−0.28	−0.19	−0.12
4.250	9.38	290	−0.34	−0.26	−0.25	−0.18
1988 Nov 20.144	0.74	117	−0.01	−0.24	−0.16	−0.21
25.144	0.58	72	−0.29	−0.13	−0.25	−0.06
26.214	0.75	272	−0.58	−0.04	−0.43	−0.22
1988 Dec 13.058	4.35	103	−0.61	−0.31	−0.24	−0.18
21.108	5.92	302	−0.65	...	...	...
21.168	5.93	314	−0.68	−0.24	−0.15	−0.17
22.020	6.08	127	−0.36	−0.40	−0.19	−0.22
28.142	7.16	294	−0.47	...	...	...
1989 Jan 27.150	10.64	280	0.35	...	...	...
28.142	10.71	122	0.51	0.14	0.26	0.14
1989 Feb 12.067	11.26	278	0.22	0.35	0.15	0.14
1989 Mar 14.061	10.47	258	0.56	0.18	0.07	...
Uzbekistan (Maydanak Observatory)						
1989 Nov 2.986	9.67	299	...	...	−0.23	...
8.900	9.01	63	...	−0.20	−0.15	−0.14
1990 Sep 27.999	9.19	39	...	...	−0.23	...
28.961	9.28	98	...	−0.09	−0.17	−0.13
1990 Oct 1.969	9.51	350	...	−0.29	−0.21	...

$$\Theta = \frac{1}{2} \arctan \frac{u}{q} . \quad (3)$$

The instrumental polarization and the zero point of position angles were determined each night using standard stars with zero and large polarization (Serkowski, Mathewson, & Ford 1975; Walborn 1968; Hsu & Breger 1982). In the spectral interval studied, the instrumental polarization did not exceed 0.05% for both spectropolarimeters and was taken into account in the reduction of our measurements. The zero point of position angles was determined with instrumental errors less than 3° in the U filter and less than 2° in the B, V, and R filters. Measurements of stars with large polarization showed the existence of a seasonally and spectrally dependent depolarization; only in the R filter could the depolarization be considered constant during the whole period of observation.

Polarimetric measurements of the Galilean satellites must be corrected for the sky's background polarization, caused by strong scattering of light from Jupiter and the Moon in the Earth's atmosphere. Therefore, depending on the circumstances, the background polarization was measured in several directions around a satellite in the orbital plane and in the plane perpendicular to the orbital plane. We have used the correction procedure developed by Botvinova & Kucherov (1980).

Each series of polarimetric observations consisted of two to six $(1–4) \times 10^6$ pulses in each filter. The actual acquisition time varied from 10 to 20 s depending on the filter, observation conditions, and the satellite observed. The acquisition time for the polarized sky background was approximately equal to the satellite exposure. For each reading, the measured dimensionless Stokes parameters q and u were corrected for instrumental errors and background sky polarization. Then, each series of readings was used to compute the average values of the dimensionless Stokes parameters $\langle q \rangle$ and $\langle u \rangle$, and, finally, the average values of the degree of polarization $\langle p \rangle$ and the position angle $\langle \Theta \rangle$ in the equatorial coordinate system and their statistical errors. In averaging q and u, we assumed that they followed the normal distribution, although this might not be strictly true (Shakhovskoy 1994). The errors in polarization degree due to uncertainties in the instrumental polarization and reductions to the standard system do not exceed 0.05%. The random errors were determined by the statistics of photons from the satellites and from the sky background, and depended on the signal accumulation time on the one hand and on the dispersion of the measured polarization parameters relative to one another on the other. The total error (the mean square error and the error of the instrumental system) in our measurements of the degree of polarization $\langle p \rangle$ in the B, V, and R filters varied from $\pm 0.04\%$ to $\pm 0.06\%$. In the U filter, the average error was about $\pm 0.1\%$. The average error in the position angle measurements was $\lesssim 10°$.

The position angle of the polarization plane relative to the plane perpendicular to the scattering plane, Θ_r, is expressed in terms of the position angle in the equatorial coordinate system, Θ, as follows;

$$\Theta_r = \Theta - (\varphi \pm 90°) , \quad (4)$$

where φ is the position angle of the scattering plane. The scattering plane essentially coincides with the intensity equator of Jupiter and thus can be easily determined for essentially any moment by interpolating daily data given in many annual catalogs. However, near the opposition ($\alpha < 1°$), the intensity equator rotates very rapidly, and its position must be computed very accurately by using the equatorial coordinates of the Sun and Jupiter in order to avoid errors in computing the position angle of the polarization plane. Apparently, Chigladze (1989) did not take this into account and erroneously determined positive polarization values at $\alpha < 1°$ for all four Galilean satellites. The small differences in the coordinates of the satellites and

TABLE 2

POLARIMETRY OF EUROPA

DATE UT	α (deg)	L (deg)	P (%) U	B	V	R
Bolivia (Tarija Observatory)						
1988 Sep 4.338	11.55	242	0.28	0.10	0.30	...
6.327	11.49	84	...	0.16	0.23	0.23
1988 Oct 1.247	9.73	90	...	0.10	0.10	0.12
2.320	9.61	199	...	...	0.18	...
4.263	9.38	36	0.34	0.21	0.10	0.14
6.318	9.13	244	0.33	0.26	−0.04	0.15
31.184	4.97	247	...	...	−0.18	...
31.222	4.97	250	−0.35	...	...	...
31.235	4.97	252	...	−0.22	−0.28	−0.25
1988 Nov 16.240	1.56	77	−0.29	−0.14	−0.12	−0.14
20.156	0.73	114	−0.12	−0.28	−0.17	−0.18
21.228	0.53	223	−0.16	...	...	...
25.245	0.59	271	−0.24	−0.24	−0.21	−0.37
1988 Dec 13.077	4.36	281	−0.33	−0.21	−0.24	−0.24
15.183	4.78	135	−0.37	−0.30	−0.18	−0.13
22.034	6.09	110	−0.60	−0.20	−0.16	−0.14
23.068	6.28	215	−0.38	−0.18	−0.24	−0.11
25.187	6.66	70	...	...	−0.19	...
1989 Jan 17.131	9.82	237	0.32	0.18	0.14	0.02
28.182	10.71	277	...	0.28	0.27	0.21
1989 Feb 1.057	10.92	310	...	0.024	0.28	...
9.030	11.21	38	...	0.21	0.15	0.12
10.090	11.22	145	...	0.09	...	...
11.017	11.24	239	0.40	0.06	0.08	0.20
17.095	11.29	134	...	0.11	0.18	0.25
1989 Mar 14.014	10.47	137	−0.43	0.22	0.10	0.20
28.990	9.27	212	...	...	0.16	...
Uzbekistan (Maydanak Observatory)						
1989 Nov 2.991	9.67	56	0.32	0.21	0.16	0.20
4.920	9.47	252	0.12	0.19	0.13	0.24
8.933	9.00	298	0.27	0.18	−0.06	0.13
12.032	8.62	253	...	−0.09	−0.16	−0.16
1990 Sep 20.950	8.57	267	...	−0.20	−0.06	−0.04
23.978	8.85	213	...	0.24	0.11	0.17
25.980	9.02	56	...	0.15	0.05	0.23
28.001	9.20	261	...	...	0.12	...
1990 Oct 1.947	9.51	300	...	0.21	0.13	0.11
1991 Feb 16.782	3.91	237	...	−0.14	−0.13	−0.18

Jupiter do not produce noticeable differences in the computed Θ_r-values.

In Tables 1–4 we present the results of our polarimetric observations of the Galilean satellites in the U, B, V, and R filters. The tables show the degree of linear polarization defined as $P = \langle p \rangle$ sign $(\cos 2\langle \Theta_r \rangle)$ (in other words, $|P| = \langle p \rangle$), and P is considered positive if the polarization plane is nearly parallel to the scattering plane and negative if the polarization plane is nearly perpendicular to the scattering plane) and also indicate the observation time (UT), the phase angle α, and the longitude L of the central meridian of the satellites. In addition, Table 5 shows unpublished polarimetric data kindly given to us by A. V. Morozhenko and measured by him in 1986 in Bolivia.

3. RESULTS

Figure 2 shows the phase-angle dependence of the degree of linear polarization P in the U, B, V, and R filters for Io, Europa, and Ganymede. Because of the small number of observations in the U filter, the data for each satellite are given for the whole visible disk. For other filters, it was possible to separate polarization data for leading and trailing hemispheres and to show them in Figure 2 using different symbols. The respective phase-angle dependence of polarization for the leading and the trailing hemispheres of Callisto is shown in Figure 3. These figures are based on Tables 1–5 and data taken from Dollfus (1975) and Chigladze (1985, 1986, 1987, 1989).

Our estimates of the degree of linear polarization for the leading and the trailing hemispheres of the Galilean satellites do not provide a detailed description of the dependence of polarization on the exact position of the satellite in its orbit. There are some indications (e.g., the significant scatter of polarization data points for both hemispheres) that the dependence of the polarization characteristics of Io, Ganymede, and Callisto on the orbital phase is complicated and needs a special investigation.

3.1. *The Phase-Angle Dependence of Polarization near Opposition*

The most interesting phenomenon observed in the B, V, and R filters for Io, Europa, and Ganymede is the steep rise of negative polarization values near opposition. Specifically, with decreasing phase angle the observed polarization

TABLE 3

POLARIMETRY OF GANYMEDE

DATE UT	α (deg)	L (deg)	P (%) U	B	V	R
Bolivia (Tarija Observatory)						
1988 Aug 6.341	11.11	95	0.10	0.26	0.22	0.10
1988 Sep 4.360	11.55	112	0.25	0.03	0.09	0.05
6.344	11.49	212	...	0.10	0.06	0.10
7.341	11.46	262	...	0.20	0.15	0.08
1988 Oct 2.302	9.62	78	0.08	−0.05	0.16	0.26
6.332	9.12	280	0.34	−0.09	0.13	0.21
7.266	9.00	327	0.31	0.14	0.11	0.06
1988 Nov 20.143	0.74	20	−0.10	−0.34	−0.34	−0.39
21.177	0.54	72	−0.05	−0.37	−0.38	−0.30
25.260	0.59	277	−0.19	−0.25	−0.26	−0.25
26.216	0.76	325	−0.36	−0.44	−0.25	−0.33
1988 Dec 13.090	4.36	97	−0.41	−0.16	−0.34	−0.12
15.196	4.78	203	−0.26	−0.18	−0.33	−0.26
21.144	5.93	143	−0.23	−0.18	−0.18	−0.28
22.234	6.12	198	−0.42	−0.26	−0.20	−0.20
23.052	6.27	239	−0.29	−0.12	−0.13	−0.14
1989 Jan 17.112	9.82	62	0.20	0.04	0.19	0.29
28.190	10.71	259	...	0.22	...	...
29.156	10.76	308	0.48	0.19	0.09	0.14
1989 Feb 1.035	10.92	94	...	0.32	0.23	0.08
9.043	11.21	135	...	...	0.21	...
11.031	11.25	236	0.35	0.19	0.23	0.33
12.089	11.26	288	0.19	0.25	0.21	0.13
23.005	11.23	183	0.25	0.13	0.10	0.15
23.041	11.23	183	...	...	0.10	...
Uzbekistan (Maydanak Observatory)						
1989 Nov 2.979	9.67	202	0.48	0.18	0.10	0.09
3.913	9.58	250	0.24	0.19	0.10	0.11
4.934	9.46	300	0.48	0.08	0.03	0.21
8.912	9.01	141	−0.29	−0.15	−0.07	−0.10
12.026	8.62	298	−0.27	−0.18	−0.04	−0.10
1990 Sep 21.936	8.66	227	...	−0.11	−0.04	−0.12
23.971	8.84	229	...	−0.07	−0.03	0.23
25.968	9.02	69	...	0.17	0.03	0.16
26.949	9.11	118	...	0.07	0.11	0.13
28.953	9.28	219	...	0.24	0.04	0.30
1991 Feb 15.931	3.74	64	...	−0.27	−0.30	−0.28
16.790	3.91	107	...	−0.26	−0.34	−0.19
19.846	4.50	260	−0.35	−0.21	−0.27	−0.16

begins to change dramatically at $\alpha \cong 1°$ and reaches maximum negative values at a phase angle of about 0°.6–0°.7 (Fig. 2). The negative polarization values in the center of the peak can exceed that at $\alpha \cong 1°$ by a factor of several. Given the observed change of polarization at $\alpha \cong 0°.2$–$0°.3$ and assuming that polarization should be expected to vanish completely at exactly the opposition, we can conclude that Io, Europa, and Ganymede exhibit, in the B, V, and R filters, rather strong and extremely narrow opposition peaks of negative polarization centered at $\alpha = 0°.6$–$0°.7$. It is hard to say whether there are any differences between the opposition peaks for different satellites or whether the peaks change with wavelength. To detect such differences, if they do exist, we need more detailed measurements of the degree of linear polarization in different filters at phase angles $\alpha < 1°$. The average values of the amplitude of the opposition polarization peaks are about 0.3%–0.4%. Unfortunately, our measurements in the U filter are not detailed enough for a reliable detection of the polarization opposition peak for any of the three satellites, except perhaps Io.

Figure 3 shows that for both the leading and the trailing hemispheres of Callisto the existence of polarization opposition peaks similar to those observed for the other Galilean satellites in the filters B, V, and R is less obvious. For both hemispheres of Callisto the observed polarization near $\alpha = 1°$ is about 0.3%–0.4% and does not seem to depend on wavelength. With further decrease of the phase angle the observed polarization tends to zero. The absence of a polarization opposition peak for Callisto can apparently be explained by the hypothesis that a significant fraction of the Callisto surface could be covered with relatively large silicate particles rather than with submicron-sized ice grains (Mandeville, Geake, & Dollfus 1980).

3.2. *Spectral Dependence of Polarization*

The multicolor polarimetry of the Galilean satellites allows us to draw several important conclusions. Figure 2 shows that for Io and Europa the regular negative polarization branch observed in the U filter is significantly deeper than that observed in other filters with minimum polarization values $P_{\min} \approx -0.6\%$ for Io and -0.4% for Europa. In

TABLE 4

POLARIMETRY OF CALLISTO

DATE UT	α (deg)	L (deg)	P (%) U	B	V	R
Bolivia (Tarija Observatory)						
1988 Aug 8.356	11.20	214	−0.46	−0.22	−0.22	−0.39
1988 Sep 5.340	11.52	94	−1.14	−0.78	−1.02	−0.79
6.308	11.49	115	...	−0.97	−1.01	−0.64
7.313	11.46	136	−1.21	−0.89	−0.86	−0.90
1988 Oct 1.260	9.73	292	...	−0.32	−0.47	−0.58
2.273	9.62	313	−0.37	−0.30	−0.75	−0.85
6.301	9.13	41	−0.87	−0.69	−0.98	−0.66
7.292	9.00	62	−1.26	−1.13	−0.85	−0.83
31.263	4.96	220	−0.66	−0.70	−0.82	−0.88
1988 Nov 16.264	1.56	207	−0.72	−0.42	−0.29	−0.48
19.257	0.90	271	−0.35	−0.38	−0.47	−0.27
20.176	0.73	291	−0.48	−0.44	−0.51	−0.40
21.196	0.54	313	−0.72	−0.52	−0.26	−0.13
25.275	0.59	44	−0.38	−0.31	−0.15	−0.33
26.233	0.76	65	−0.25	−0.22	−0.15	−0.50
1988 Dec 13.107	4.36	71	−0.98	−1.02	−0.94	−0.71
15.213	4.78	116	−0.87	−1.01	...	...
21.156	5.93	244	−0.77	−0.53	−0.46	−0.64
22.052	6.09	263	−0.57	−0.64	−0.71	−0.76
23.013	6.27	284	−0.66	−0.89	−0.61	−0.59
25.192	6.63	330	...	...	−0.53	...
1989 Jan 17.037	9.81	107	−0.89	−0.88	−1.06	−0.94
28.070	10.71	346	−0.28	−0.64	−0.82	−0.78
1989 Feb 1.044	10.92	71	−0.80	−0.80	−1.00	−1.10
1.085	10.92	72	...	...	−0.98	...
9.051	11.21	243	...	−0.10	−0.21	...
10.096	11.23	265	...	−0.27	−0.45	−0.32
11.060	11.24	286	−0.60	...	...	...
12.111	11.26	308	...	−0.29	−0.64	−0.42
17.129	11.29	57	−0.50	−0.75	−0.75	...
18.000	11.28	76	−0.80	−0.74	−0.87	−1.08
1989 Mar 14.017	10.47	231	−0.74	−0.29	−0.23	−0.55
23.977	9.70	84	...	...	−0.90	...
28.007	9.36	171	−1.15	−0.87	−0.91	−0.80
28.333	9.27	192	...	−0.58	−0.68	−1.02
1989 Apr 4.982	8.58	342	...	−0.67	−0.65	−0.63
24.965	6.30	48	...	−0.64	...	...
Uzbekistan (Maydanak Observatory)						
1989 Nov 2.961	9.67	196	...	−0.82	−0.64	−0.92
3.917	9.58	216	−0.51	−0.49	−0.45	−0.58
4.944	9.46	238	−0.26	−0.52	−0.51	−0.72
8.958	9.00	325	−0.60	−0.64	−0.52	−0.67
12.007	8.62	32	−1.05	−1.04	−0.74	−1.09
1990 Sep 20.964	8.57	278	...	−0.43	−0.47	−0.46
21.944	8.66	299	...	−0.35	−0.59	−0.52
23.988	8.85	343	...	−0.58	−0.58	−0.59
25.974	9.02	24	...	−0.98	−0.87	−0.90
26.957	9.11	45	...	−1.04	−0.91	−1.03
27.996	9.19	67	...	...	−0.96	...
28.969	9.28	88	...	−1.05	−0.92	−1.04
1990 Oct 1.960	9.51	152	...	−0.77	−0.95	−0.72
1991 Feb 15.945	3.74	227	...	−0.68	−0.64	−0.69
16.799	3.91	245	...	−0.62	−0.60	−0.58
19.834	4.50	310	−0.65	−0.70	−0.60	−0.73
19.863	4.50	311	−0.60	−0.70	−0.64	−0.73

other filters, the spectral dependence of P_{min} for the regular negative branch is weaker but still exists (Fig. 4). At the same time, Ganymede shows a much weaker spectral variability of P_{min}, even in the U filter. The smallest $|P_{min}|$ values for all three satellites are observed in the V filter.

As Figure 4 shows, the P_{min} values for Io, Europa, and Ganymede are somewhat different for the leading and the trailing hemispheres: for the leading hemisphere, the regular negative polarization branch is systematically shallower than for the trailing hemisphere. This difference can be within measurement errors for Io and Europa but is well pronounced for Ganymede. Indeed, whereas the $|P_{min}|$ values for the trailing hemisphere of Ganymede in the B, V, and R filters are about 0.40%, 0.32%, and 0.32%, respectively, those for the leading hemisphere are about 0.25%, 0.22%, and 0.20%.

TABLE 5

POLARIMETRY OF GALILEAN SATELLITES BY A. V. MOROZHENKO

Date UT	Satellite	α (deg)	L (deg)	P (%) U	B	V	R
1986 Sep 9.253......	Io	0.47	251	−0.38	−0.38	−0.32	−0.26
9.314......	Europa	0.46	160	...	...	−0.28	...
9.155......	Ganymede	0.49	9	−0.14	−0.25	−0.21	−0.24
9.153......	Callisto	0.49	322	−0.34	−0.43	−0.29	−0.24

The positive polarization values at around $\alpha = 11°$ in the U filter are systematically larger than in the other filters (Fig. 2). For Io the U values of positive polarization are close to 0.40%–0.45%; for Europa the U, B, V, and R positive polarization values are close to 0.35%, 0.25%, 0.15%, and 0.20%, respectively; and for Ganymede they are close to 0.25%, 0.25%, 0.20%, and 0.20%. Although these numbers are approximate, they show that the spectral dependences of P_{min} and $P(11°)$ are similar. Also, it should be noted that the positive polarization branch for the trailing hemispheres in the B, V, and R filters seems to go a little higher than for the respective leading hemisphere.

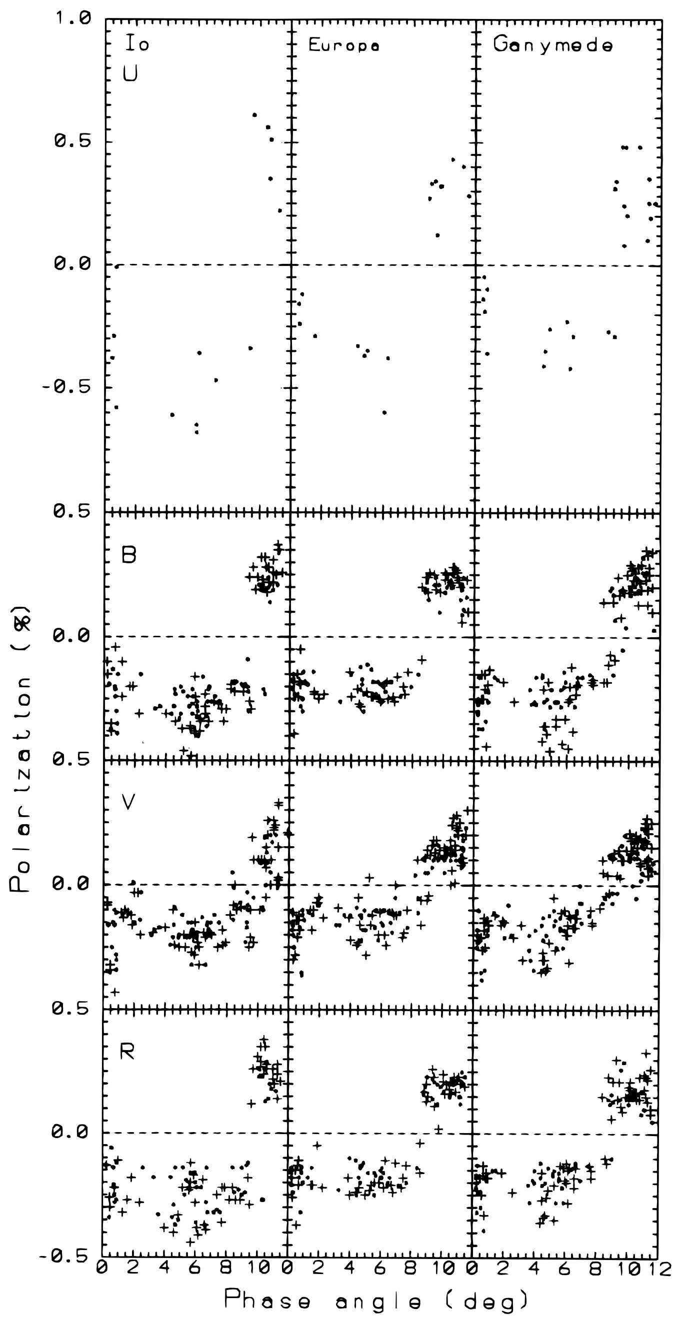

FIG. 2.—Phase-angle dependence of the degree of linear polarization P (%) in the U, B, V, and R filters for Io, Europa, and Ganymede. The U filter data are shown for the whole disk, while the BVR data are shown separately for the leading (*filled circles*) and the trailing (*plus signs*) hemispheres.

In contrast to P_{min}, the phase angle of minimum polarization α_{min} for the regular negative polarization branch of Io and Europa does not show a systematic wavelength dependence. Even if this dependence does exist, it is weak and cannot be clearly detected from the data shown in Figure 2. Given the scatter of data points, we can conclude that for Io $\alpha_{min} = 6\overset{\circ}{.}0 \pm 0\overset{\circ}{.}2$, while for Europa $\alpha_{min} = 5\overset{\circ}{.}5 \pm 0\overset{\circ}{.}2$. Note that these values of α_{min} were derived by averaging estimates obtained separately for each filter and each hemisphere, and $\pm 0\overset{\circ}{.}2$ is the dispersion of these values. The real errors in α_{min} can therefore be (much) larger than $\pm 0\overset{\circ}{.}2$.

For Ganymede, α_{min} seems to change with wavelength. In the U filter, the whole-disk α_{min} value is close to $5\overset{\circ}{.}0 \pm 0\overset{\circ}{.}2$. Approximately the same value is observed for both the leading and the trailing hemispheres of Ganymede in the B filter. However, in the V and R filters, α_{min} is somewhat smaller and is close to $4\overset{\circ}{.}5 \pm 0\overset{\circ}{.}2$. Overall, the α_{min} values for Ganymede seem to be smaller than those for Io and Europa.

According to Veverka (1971) and Dollfus (1975), the leading and the trailing hemispheres of Callisto exhibit much larger polarization differences than those of other Galilean satellites. The data shown in Figure 3 corroborate this result and can be used in reaching more specific conclusions. The minimum negative polarization value P_{min} for the trailing hemisphere is nearly wavelength independent and is within the range −0.60% to −0.65% (Fig. 4). The phase angle of minimum polarization α_{min} is close to $6\overset{\circ}{.}0 \pm 0\overset{\circ}{.}2$ and is also essentially wavelength independent. Apparently, the inversion point α_{inv} (the phase angle at which polarization changes sign) also does not depend on wavelength and is in the range 12°–13°.

On the other hand, if we assume that the inversion point for the leading hemisphere of Callisto is approximately 12°, then P_{min} in the B, V, and R filters is within the range −0.85% to −0.90% (Fig. 4). At the same phase angle, the degree of linear polarization in the U filter reaches the value −1.05%. Thus, the leading and the trailing hemispheres of Callisto indeed show significant differences in the degree of linear polarization and its spectral dependence, as well as in the phase angle of minimum polarization.

It should be noted that individual measurements are widely spread and often depart by more than ±0.1% from the best-fitting curves. Most probably, the scatter of individual measurements can be related to the differences in

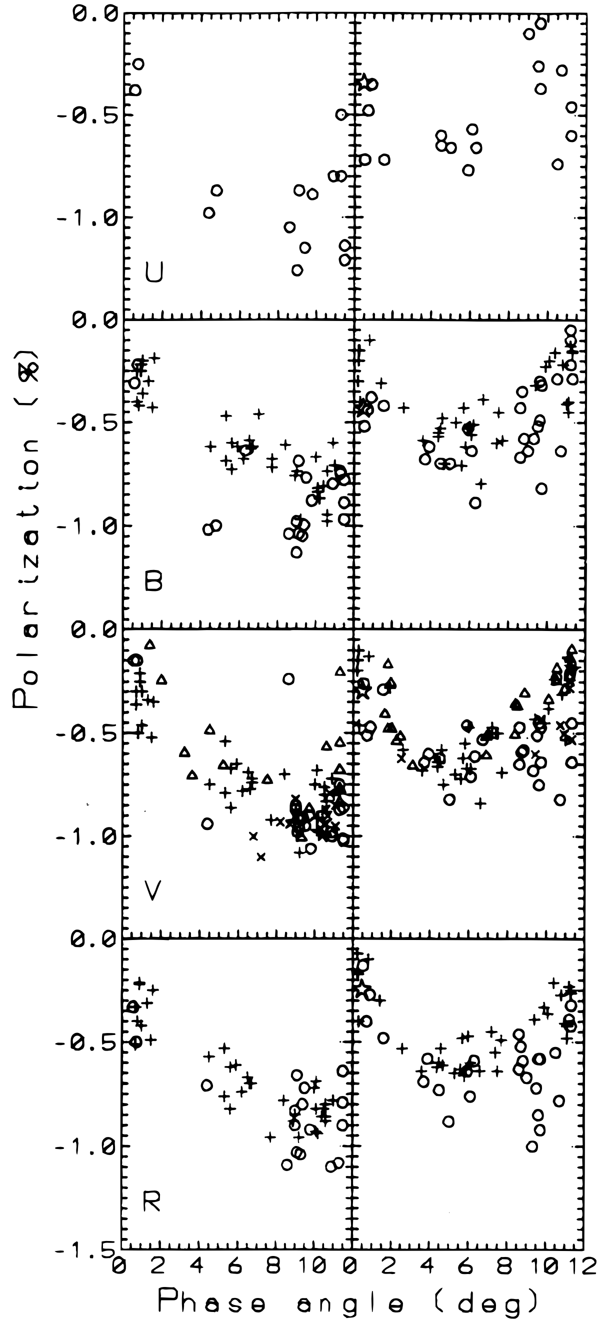

FIG. 3.—Phase-angle dependence of the degree of linear polarization P (%) in the U, B, V, and R filters for the leading (*left panels*) and the trailing (*right panels*) hemispheres of Callisto. The data are taken from Chigladze (1985, 1986, 1987, 1989) (*plus signs*), Dollfus (1975) (*triangles*), and Tables 4 and 5 (*open circles*).

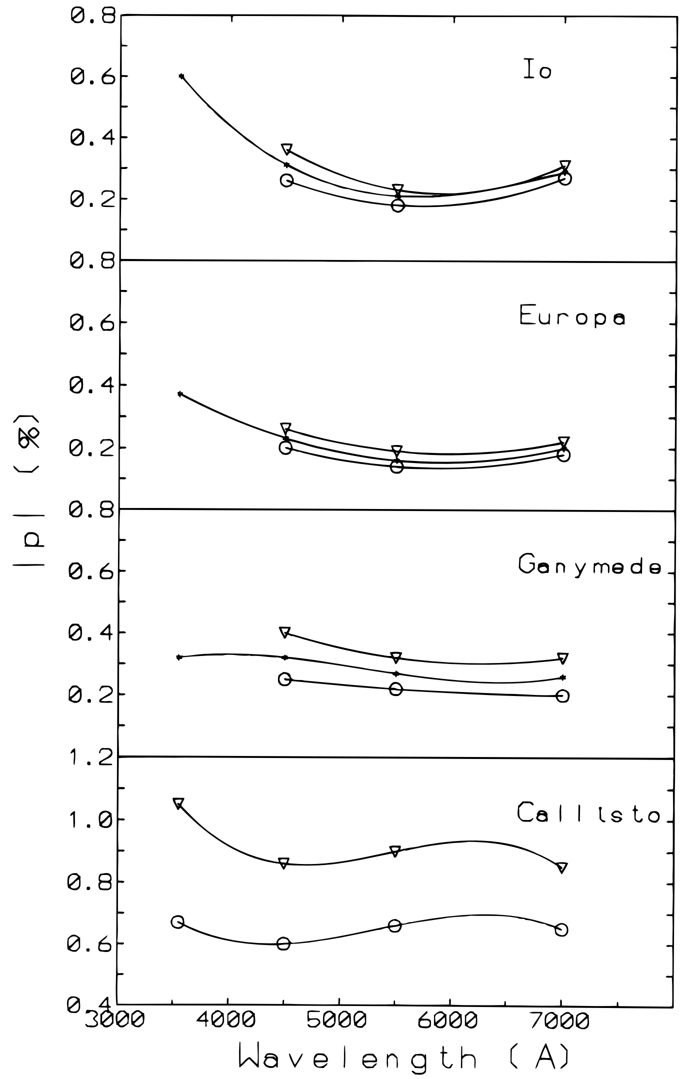

FIG. 4.—Spectral dependence of $|P_{\min}|$ for the Galilean satellites of Jupiter. For Io, Europa, and Ganymede, data are shown separately for the trailing (*inverted triangles*) and the leading (*open circles*) hemispheres as well as for the whole disk (*asterisks*). For Callisto, data are given for the leading (*inverted triangles*) and the trailing (*open circles*) hemispheres.

measurement accuracy for different authors and the visual aspect of the satellite seen in the telescope. Besides the instrumental errors, the proximity of Jupiter causes a scattered-light background that is difficult to correct for with sufficient accuracy. In addition, the scatter of data points might be attributable to local variations in the surface properties with orbital longitude or to possible real variations in scattering properties. As already mentioned, there are some indications that the dependence of the polarization characteristics of Callisto on the orbital phase is complicated and needs a special investigation (see, e.g., Mandeville, Geake, & Dollfus 1980).

3.3. *The Behavior of Polarization near the Inversion Angle*

It has long been known that for essentially all observed ASSBs, the polarization plane at small phase angles coincides with the scattering plane (so that the angle between the polarization plane and the normal to the scattering plane is $\Theta_r = 90°$), while at the phase angle where polarization changes sign, the polarization plane steeply changes its orientation by 90° and becomes perpendicular to the scattering plane ($\Theta_r = 0$). This critical phase angle is traditionally called the inversion angle ($\alpha_{\rm inv}$, Fig. 1). In the Stokes parameter representation of polarization, such linearly polarized radiation is fully described by the second Stokes parameter, q, which, in the reference frame associated with the scattering plane, is $q = P = p \cos 2\Theta_r$, where p is the observed degree of polarization. For $\alpha < \alpha_{\rm inv}$, q is always negative ($\Theta_r = 90°$, so-called negative polarization), whereas for $\alpha > \alpha_{\rm inv}$ the second Stokes parameter is always positive ($\Theta_r = 0°$, or positive polarization). At the inversion point ($\alpha = \alpha_{\rm inv}$), p is equal to zero, and polarization changes its sign. Obviously, the third Stokes parameter, $u = p \sin 2\Theta_r$ is equal to zero.

In order to investigate the polarization behavior of the Galilean satellites near the inversion angle, we have analyzed in detail the phase curves of the absolute value of the degree of linear polarization $|P|$ and the position angle of the polarization plane Θ_r for Io, Europa, and Ganymede. To this end, we have plotted the whole-disk values of $|P|$ and Θ_r versus phase angle for each of the filters *B*, *V*, and *R*. In analyzing these plots, we need to take into account the following factor. If one has *N* independent measurements of the degree of linear polarization for unpolarized light ($P = 0$), then, because of the finite accuracy of the measurements, all measured values of the absolute value of *P* will be nonzero: $|P_i| > 0$. Therefore, the average measured value

$$\langle |P| \rangle = \frac{1}{N} \sum_{i=1}^{N} |P_i| > 0 \tag{5}$$

will be a measure of the measurement accuracy rather than of the actual polarization value, unless $\langle |P| \rangle$ significantly exceeds the measurement error.

Figure 5 shows the phase-angle dependences of $|P|$ and Θ_r for Io, Europa, and Ganymede in the *B* and *V* filters. In this figure we also used *V* filter data from Dollfus (1975), which we found to be systematically understated relative to our measurements as well as to the measurements of Chigladze (1985, 1986, 1987, 1989). It is clear that in all cases the average $|P|$ values systematically exceed the average measurement error. This indicates that the radiation reflected by Io, Europa, and Ganymede near the inversion angle is polarized and that this polarization is not caused by the finite accuracy of our measurements. On the other hand, the measured Θ_r values for $\alpha < \alpha_{inv}$ and $\alpha > \alpha_{inv}$ do not differ from 90° or 0°, respectively, within the measurement accuracy. Near the inversion angle ($|\alpha - \alpha_{inv}| \leq 0^\circ.5$), the scatter of the measured Θ_r values is somewhat larger than the measurement accuracy, but it is clear that the rotation of the polarization plane by 90° occurs nearly stepwise. More specifically, this means that the rotation of the polarization plane occurs within an interval $\alpha_{inv} \pm \Delta\alpha$, where the interval semiwidth $\Delta\alpha$ does not exceed $0^\circ.1$ or $0^\circ.2$. Therefore, the process of the polarization plane's rotation cannot be resolved given the accuracy of our measurements.

We have found that near the inversion angle, $|P|$ for Io in the *B* and *R* filters is close to 0.20%–0.25% and is lower in the *V* filter (about 0.12%). For Europa and Ganymede, $|P|$ in the *V* filter is close to 0.15%–0.20% and 0.12%, respectively. The rotation of the scattering plane in the *B*, *V*, and *R* filters occurs in a similar manner.

We have already shown in Figure 2 the negative and the positive branches of the polarization phase curves for Io, Europa and Ganymede. One can observe a noticeable gap between these branches in the *B*, *V*, and *R* filters. This

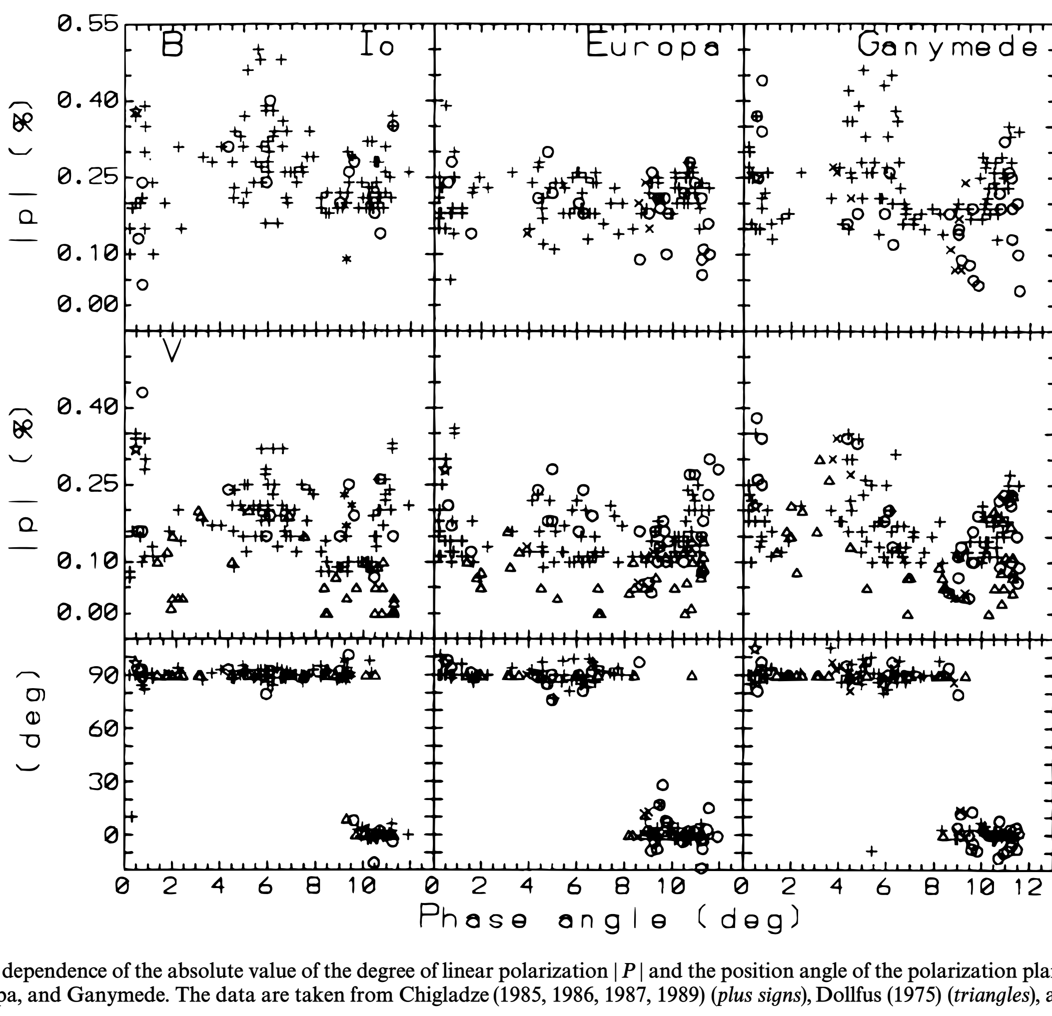

FIG. 5.—Phase dependence of the absolute value of the degree of linear polarization $|P|$ and the position angle of the polarization plane Θ_r in the *B* and *V* filters for Io, Europa, and Ganymede. The data are taken from Chigladze (1985, 1986, 1987, 1989) (*plus signs*), Dollfus (1975) (*triangles*), and Tables 1–3 (*open circles*).

gap is caused by the fact, that, in a narrow but nonetheless finite range of phase angles centered at $\alpha_{\rm inv}$, polarization does not disappear completely but rather retains nonzero values. The existence of nonzero polarization near the inversion angle means that the second and third Stokes parameters never vanish simultaneously.

The inversion angle $\alpha_{\rm inv}$ can be determined either by using the measured phase-angle dependence of the degree of linear polarization $P(\alpha)$ near phase angles where it changes sign, or by using the phase-angle dependence of the position angle of the polarization plane $\Theta_r(\alpha)$. However, the first method results in significantly poorer accuracy than the second method. By using the second method, we have found that $\alpha_{\rm inv}$ for Io, Europa, and Ganymede in the *B*, *V*, and *R* filters are nearly wavelength independent and equal to $10\overset{\circ}{.}0 \pm 0\overset{\circ}{.}2$, $8\overset{\circ}{.}6 \pm 0\overset{\circ}{.}3$, and $8\overset{\circ}{.}8 \pm 0\overset{\circ}{.}2$, respectively. For the trailing hemisphere of Callisto, the inversion angle also seems to be wavelength independent and is in the range 12°–13°.

4. DISCUSSION

In addition to Io, Europa, and Ganymede, a rather pronounced polarization opposition effect at $\alpha < 1°$ was clearly observed for the B ring of Saturn (Lyot 1929; Dollfus 1979; Johnson et al. 1980). An extensive investigation of this effect was led by Dollfus (1979) (see also Dollfus 1984, 1996), who was able to measure the degree of linear polarization of the B ring at phase angles down to $0\overset{\circ}{.}08$. Given the importance of this investigation, we reproduce, in Figure 6, the phase-angle dependence of polarization measured for the ring cusps (Dollfus 1984). The polarization phase curve clearly shows two minima: at $\alpha \approx 4°$–$5°$ with $P_{\rm min} \approx -0.43\%$ and at $\alpha \approx 0\overset{\circ}{.}7$ with $P_{\rm min} = -0.4\%$. With $\alpha \rightarrow 0$, the absolute value of polarization sharply decreases and ultimately vanishes. Polarimetric measurements of Saturn's rings by Lyot (1929) and Johnson et al. (1980) taken at phase angles from almost 0° up to 6° do not show two well-separated polarization minima analogous to those seen in Figures 2 and 6. However, the observed polarization phase curves at $\alpha < \alpha_{\rm inv}$ are highly asymmetric and differ dramatically from the usual negative polarization branch being zero at $\alpha = 0°$, rapidly decreasing with increasing α, and nearly reaching maximum negative values at phase angles smaller than 1°.

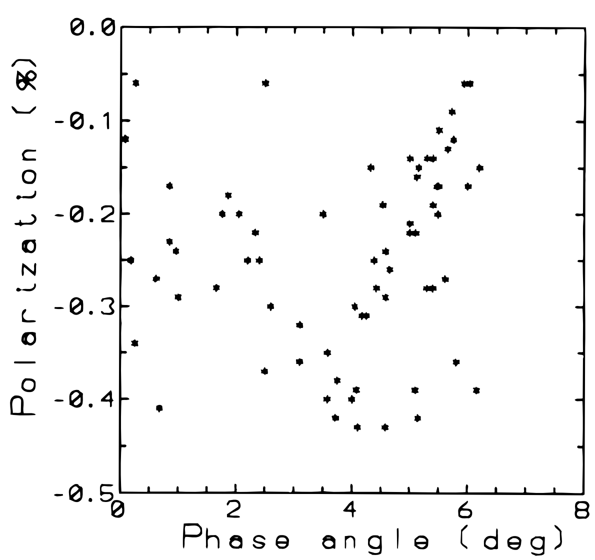

FIG. 6.—Phase-angle dependence of the degree of linear polarization for the cusps of the B ring of Saturn of $\lambda = 550$ nm (Dollfus 1984).

Mishchenko (1993) has used the rigorous theory of coherent backscattering (Barabanenkov et al. 1991; Ozrin 1992) to show that regolith surfaces composed of nonabsorbing or weakly absorbing, subwavelength-sized grains produce a sharp asymmetric peak of negative polarization at very small phase angles (Fig. 7). Since different parts of the surfaces of ASSBs can be covered by grains of different size, the coherent negative polarization peak produced by the smallest grains can be superposed on the regular negative polarization branch produced by larger grains and/or by surface irregularities. Depending on the values of the parameters $\alpha_{{\rm min},R}$, $P_{{\rm min},R}$, $\alpha_{{\rm min},C}$, and $P_{{\rm min},C}$, which specify the shape of the regular negative polarization branch (subscript *R*) and the coherent peak of negative polarization (subscript *C*; Fig. 7), the resulting polarization curve can have different shapes at small phase angles. In particular, if $\alpha_{{\rm min},R}$ is significantly larger than $\alpha_{{\rm min},C}$, the resulting polarization curve will have two well-separated negative polarization minima (Figs. 2 and 6). Otherwise, the curve will have a single, wide, and highly asymmetric minimum similar to that observed by Lyot (1929) and Johnson et al. (1980) for Saturn's rings. However, in all cases when $|P_{{\rm min},C}|$ exceeds measurement errors, the resulting polarization curve will be asymmetric and will show a sharp change of polarization at extremely small phase angles.

A fundamental result of the theory of coherent backscattering is that the sharp peak of negative polarization at very small phase angles is accompanied by a similarly narrow intensity peak centered exactly at the backscattering direction (Mishchenko 1991, 1992a, 1993). Therefore, the fact that an extremely narrow opposition intensity peak has indeed been observed for Saturn's rings (Franklin & Cook 1965) and Europa (Thompson & Lockwood 1992) provides strong support for the hypothesis that the same submicron-sized grains and the same optical mechanism (coherent backscattering) are responsible for both the photometric and the polarization opposition effects observed for Galilean satellites and Saturn's rings (Mishchenko & Dlugach 1992; Mishchenko 1993). Importantly, the presence of such small grains in the outer solar system follows from the interpretation of the radial

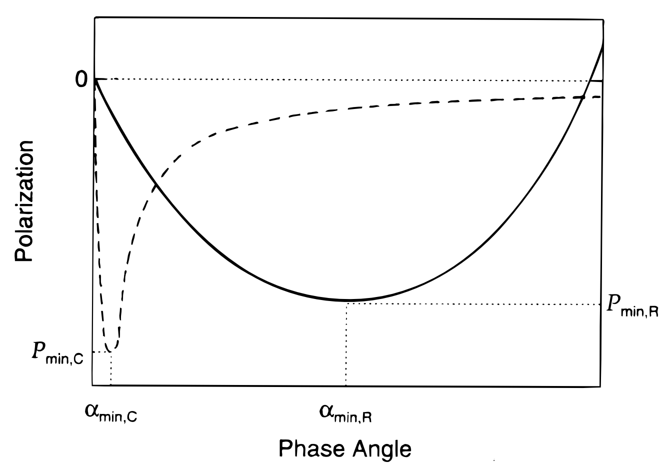

FIG. 7.—Comparison of the regular negative polarization branch (*solid curve, subscript R*) and the negative polarization peak produced by coherent backscattering (*dashed curve, subscript C*).

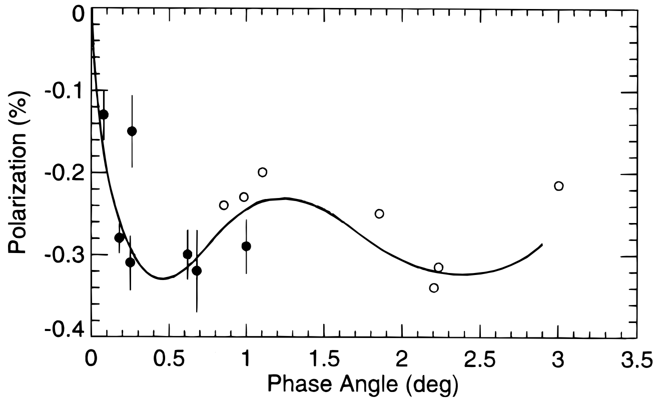

FIG. 8.—Phase dependence of the degree of linear polarization for the A and B rings of Saturn measured by Dollfus (1997, private communication) (see text). The curve shows a tentative interpretation of the measurements (cf. Fig. 7).

"spokes" in Saturn's rings (Doyle & Grün 1990) and can apparently explain the spikelike photometric opposition peaks exhibited by icy Uranian satellites (Brown & Cruikshank 1983; Goguen, Hammel, & Brown 1989; Mishchenko 1992b).

Recently, Dollfus (1997, private communication) has reanalyzed the data shown in Figures 5 and 6 of Dollfus (1979), which have turned out to be especially suitable for the search for the coherent polarization opposition effect for the following two reasons. First, the coherent polarization opposition effect predicts a direction of polarization always perpendicular to the scattering plane, whereas ordinary reflectance polarization is influenced by local ring anisotropies. Therefore, an important advantage of these measurements is that they permit following, day by day, the evolution of the direction of polarization with respect to the scattering plane. Second, the large number of measurements covered the whole ring system and allowed, by averaging, the reduction of the effect of local variations in Saturn's ring polarization and the derivation of a reliable estimate of measurement accuracy. The analysis results are summarized in Table 6 and Figure 8 (*filled circles*). In addition, open circles in Figure 8 show photoelectric measurements at the rings' cusps at 580 nm, taken from Figure 3 of Dollfus (1996). The latter measurements are for phase angles close to and larger than 1° and are probably not significantly influenced by coherent backscattering. As expected from the theory of coherent backscattering, Figure 8 clearly shows a narrow minimum of polarization centered at a phase angle of $\alpha \approx 0\overset{\circ}{.}5$–$0\overset{\circ}{.}7$ and superimposed on a relatively smooth polarization background.

There is evidence that, in addition to Saturn's rings and Jupiter's Galilean satellites, a pronounced peak of polarization at phase angles smaller than 1° is also exhibited by asteroids 55 Pandora (Lupishko et al. 1994), and 64 Angelina (Kiselev, Shakhovskoy, & Efimov 1996). *V* filter meaurements by Lupishko et al. (1994) suggest that the negative polarization for 55 Pandora at $\alpha = 0\overset{\circ}{.}3$ almost reaches the value -0.50%. Kiselev et al. (1996) have found that the polarization phase curves for 64 Angelina in the *R* and *I* filters have a second inversion at $\alpha \approx 1\overset{\circ}{.}5$ and a positive polarization maximum ($P \approx 0.5\%$) at $\alpha \approx 0\overset{\circ}{.}5$, whereas at $\alpha = 0\overset{\circ}{.}12$ polarization is again negative and almost reaches the value -0.6%. Usually, for asteroids the regular negative polarization minimum ($P_{\min,R} \approx -1.0\%$) is observed at $\alpha_{\min,R} \approx 8°$ (Zellner & Gradie 1976). The results of Lupishko et al. (1994) and Kiselev et al. (1996) seem interesting and need to be further verified by more accurate and detailed measurements, although it is clear that high-quality photometric and polarimetric observations at phase angles less than 1° are extremely difficult. The detection of the polarization opposition effect for 64 Angelina would be especially interesting, since this bright asteroid exhibits a strong photometric opposition effect (Harris et al. 1989) that can be adequately explained by the coherent backscattering mechanism (Mishchenko & Dlugach 1993).

Geake & Geake (1990) have performed a laboratory study of the dependence of the polarization phase curve on the size of the grains forming a reflecting surface. They have used several Al_2O_3 powders with varying average grain size and found that particles with sizes comparable to and smaller than the wavelength produce a narrow and sharp peak of negative polarization at nearly zero phase angles. Specifically, the polarization, being zero at $\alpha = 0°$, reaches its maximum negative value at $\alpha < 1°$. Almost exactly the same peak was measured much earlier by Lyot (1929) for a particulate surface composed of microscopic magnesium oxide grains. The peaks measured by Lyot (1929) and Geake & Geake (1990) are quite similar to the negative polarization peaks exhibited by Io, Europa, and Ganymede at $\alpha < 1°$ and also to the peak seen in Figures 6 and 8. The difference between the polarization phase curves measured for the microscopic MgO and Al_2O_3 powders and those observed for the Galilean satellites and Saturn's rings is that the laboratory measurements do not show a second negative polarization minimum between $\alpha = 1°$ and the inver-

TABLE 6

POLARIMETRIC MEASUREMENTS OF SATURN'S RING B AT SMALL PHASE ANGLES
(Dollfus 1997, private communication)

Date	Time (hh:mm)	Phase Angle (deg)	P (%)	rms (%)	Number of Areas Measured
1972 Dec 4	00:20	−0.62	−0.30	±0.030	9
1972 Dec 7	20:00	−0.25	−0.31	±0.033	9
1972 Dec 9	20:00	0.18	−0.28	±0.018	10
1972 Dec 14......	20:00	0.68	−0.32	±0.050	10
1972 Dec 17......	22:30	1.00	−0.29	±0.033	10
1976 Jan 17	21:40	−0.26	−0.15	±0.044	10
1976 Jan 19	21:00	−0.08	−0.13	±0.030	6

sion angle. It is clear, however, that this difference can be easily explained by the fact that each laboratory sample consisted of a relatively narrow, monomodal particle polydispersion, whereas the polarization curves observed for the ASSBs are a superposition of contributions reflected by different parts of highly heterogeneous natural surfaces composed of particles with different average sizes. The smallest, wavelength- or subwavelength-sized grains produced the coherent negative polarization peak, while coarser grains and/or surface irregularities were responsible for polarization at larger phase angles.

As discussed in § 3.3, our observations may suggest that the degree of polarization $\langle p \rangle$ of light reflected by the Galilean satellites can be nonzero at the inversion angle. Whereas our measurements show that the position angle of the polarization plane Θ_r is equal to 90° for $\alpha < \alpha_{inv}$ and to 0° for $\alpha > \alpha_{inv}$, they cannot say anything about the behavior of the polarization plane within a narrow interval of phase angles centered at α_{inv}. Such residual polarization, if it does exist, may be produced by inhomogeneities or anisotropies of the satellite surfaces. However, a quantitative interpretation of this effect requires an accurate correction for the illumination of the satellites by the light scattered from Jupiter and will be discussed in a separate paper.

Apparently, the same residual polarization was observed for the asteroid 4179 Toutatis (Lupishko et al. 1995). Specifically, *UBVRI* polarimetry of this asteroid performed in 1992 and 1993 showed that at the inversion angle the polarization was close to 1%, and Θ_r was different from 0° or 90° in all spectral bands studied. This may suggest that the rotation of the polarization plane near the inversion angle occurs smoothly rather than stepwise, as would be expected of an ASSB. Importantly, the range of phase angles within which the polarization plane rotated by 90° was at least several degrees. The smooth rotation of the polarization plane near the inversion angle means that both the second and the third Stokes parameters, $\langle q \rangle$ and $\langle u \rangle$, do not vanish simultaneously. Clearly, at $\Theta_r = 45°$ (or 135°) the absolute value of $\langle u \rangle$ reaches its maximum value and becomes equal to the observed degree of linear polarization $\langle p \rangle$, whereas $\langle q \rangle$ vanishes and changes its sign.

These results raise the question of why essentially all previous observations of ASSBs did not show any peculiar behavior of polarization at the inversion point. There are two possible answers: on the one hand, the surface of Toutatis could be especially heterogeneous and, therefore, cause a smooth rather than stepwise rotation of the polarization plane; on the other hand, the measurement by Lupishko et al. (1995) could be incorrect.

Somewhat earlier, Kvartskhelia (1988) studied the behavior of the polarization plane at the inversion angle for different parts of the lunar surface. He found that just before the inversion, when the degree of polarization $\langle p \rangle$ decreases to 0.15%–0.10%, the polarization plane deviates significantly from its standard orientation. He concluded, however, that this effect was caused by measurement errors, and that the polarization plane rotates stepwise at the inversion angle. Kvartskhelia (1988) found the same effect in laboratory measurements of lunar samples but again concluded that the effect was an artifact of nonzero measurement errors.

Laboratory measurements also do not provide an unambiguous picture of the behavior of the polarization plane near the inversion angle. For example, Kochan (1964), Morozhenko (1966), Degtjarev, Kolokolova, & Morozhenko (1990), and Degtjarev et al. (1991) have found that for all their samples, the rotation of the polarization plane occurs smoothly within a range of phase angles $\Delta\alpha$ which can be as small as a few tenths of a degree and as large as almost 10°. On the other hand, Lyot (1929), Dollfus & Titulaer (1971), Pellicori (1971), and Shkuratov, Melkumova, & Badyukov (1988) concluded that the rotation of the polarization plane for terrestrial samples as well as for ASSBs occurs stepwise and that the polarization state of the scattered light is fully described by the second Stokes parameter. Obviously, these quite different results, obtained for similar (and sometimes the same) samples, require an explanation. One could hypothesize that the value of polarization and the behavior of the polarization plane near the inversion angle are most likely determined by the presence or absence of an optical anisotropy of the scattering surface. Unfortunately, we are not aware of any theoretical investigation of this important problem.

5. CONCLUSIONS

Our experimental study of the degree of linear polarization and the orientation of the polarization plane for the Galilean satellites of Jupiter has led to the following conclusions.

1. The main result of this paper is that the *BVR* polarization phase curves of Io, Europa, and Ganymede exhibit the polarization opposition effect as a sharp peak of negative polarization centered at $\alpha \approx 0.^\circ6$–$0.^\circ7$ and superposed on the regular negative polarization branch. For Europa, the ratio of the absolute value of polarization in the center of the peak to $|P_{min}|$ of the regular negative polarization branch is almost 1.6, whereas for Io and Ganymede this ratio is smaller and is close to 1.1–1.3. The angular semiwidth of the opposition polarization effect (about $0.^\circ3$) is comparable to that of the photometric opposition effect observed for Europa, thus indicating that both features are likely to be produced by the coherent backscattering mechanisms (cf. Mishchenko 1993). For Callisto, the sharp negative polarization peak at $\alpha < 1°$ may be absent. This can, apparently, be explained by the dominance of large silicate grains on the Callisto surface (Mandeville et al. 1980).
2. Io, Europa, and Ganymede may exhibit a noticeable polarization at the inversion angle. If this effect is real, it means that the second and third Stokes parameters never vanish simultaneously and that the rotation of the polarization plane by 90° at the inversion angle occurs smoothly rather than stepwise, albeit fast. The range of phase angles within which the rotation occurs does not exceed a few tenths of a degree.
3. The *U*-filter values of $|P_{min}|$ for Io and Europa are close to 0.60% and 0.47%, respectively, and exceed the respective *BVR* values by a factor of almost 2. For Ganymede, as well as for the leading and the trailing hemispheres of Callisto, the spectral variability of $|P_{min}|$ is less pronounced.
4. The *BVR* polarization in the minimum for the trailing hemispheres of Ganymede, and perhaps Io and Europa, is systematically stronger than for the respective leading hemispheres. For Callisto, the leading hemisphere polarization is significantly stronger than the trailing hemisphere polarization.
5. The inversion angles for Io, Europa, and Ganymede are nearly wavelength independent and close to $10.^\circ0$, $8.^\circ6$,

and 8°.8, respectively. The inversion angle for the trailing hemisphere of Callisto is also wavelength independent and is close to 12°–13°.

6. The angles of minimum polarization for the regular negative polarization branches of Io, Europa, and Ganymede are essentially wavelength independent and close to 6°, 5°.5, and 4°.8. For the trailing hemisphere of Callisto, α_{min} is close to 6°.0 and is also wavelength independent. For the leading hemisphere, α_{min} is, apparently, close to 11°, and it is difficult to conclude anything about its spectral variability.

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